Modeling Long-Wavelength Thermal Emissions from Non-Spherical Circumstellar Media:

Applications to structured envelopes of hot massive stars

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Emphasis on long-wavelengths and unresolved sources,

with select complementary multi-wavelength diagnostics

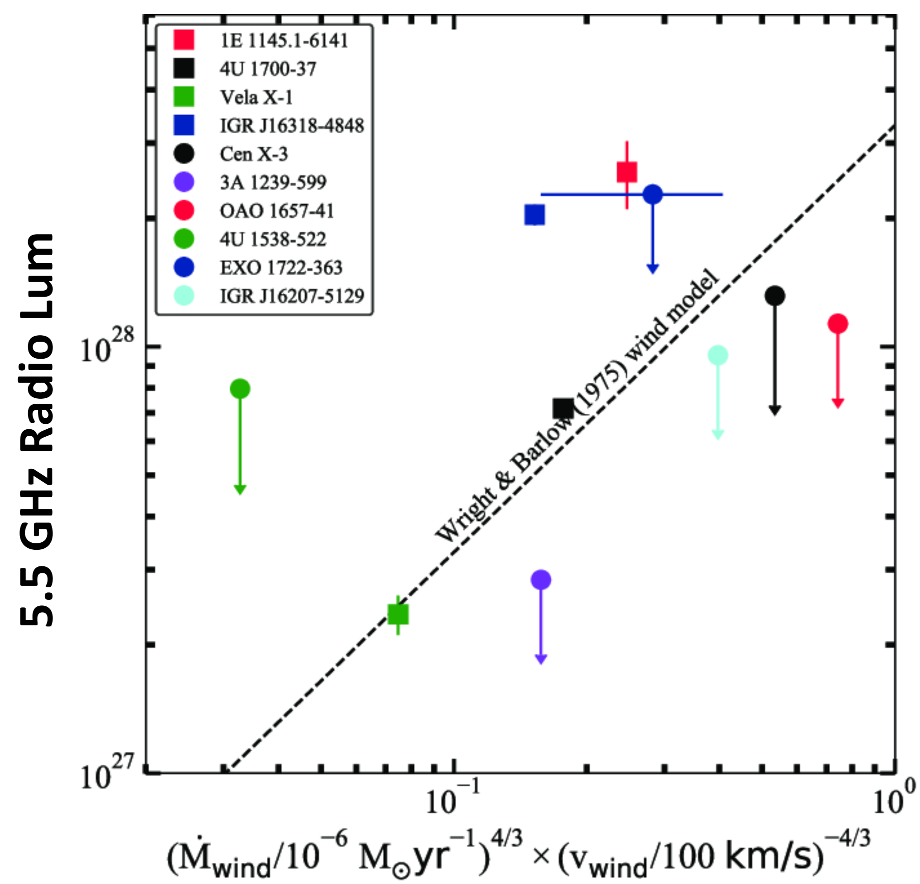
Setting the stage: The canonical result

- 1975: Panagia & Felli and Wright & Barlow
  - Spherical wind at terminal speed with inverse square density and ff
  - Blackbody radiation and isothermal
  - Classic result of SED spectrum $f_\nu \sim \lambda^{-0.6}$

    This is a -2/3 slope with correction for the Gaunt factor.
  - SED slope comes from Rayleigh-Jeans B_ν combined with growing pseudo-photosphere R_ν
- The slope comes from an **isophotal growth rate**, for given source function, and luminosity can give the wind mass-loss rate

van den Eijnden+ 2021

A new radio census of neutron star X-ray binaries



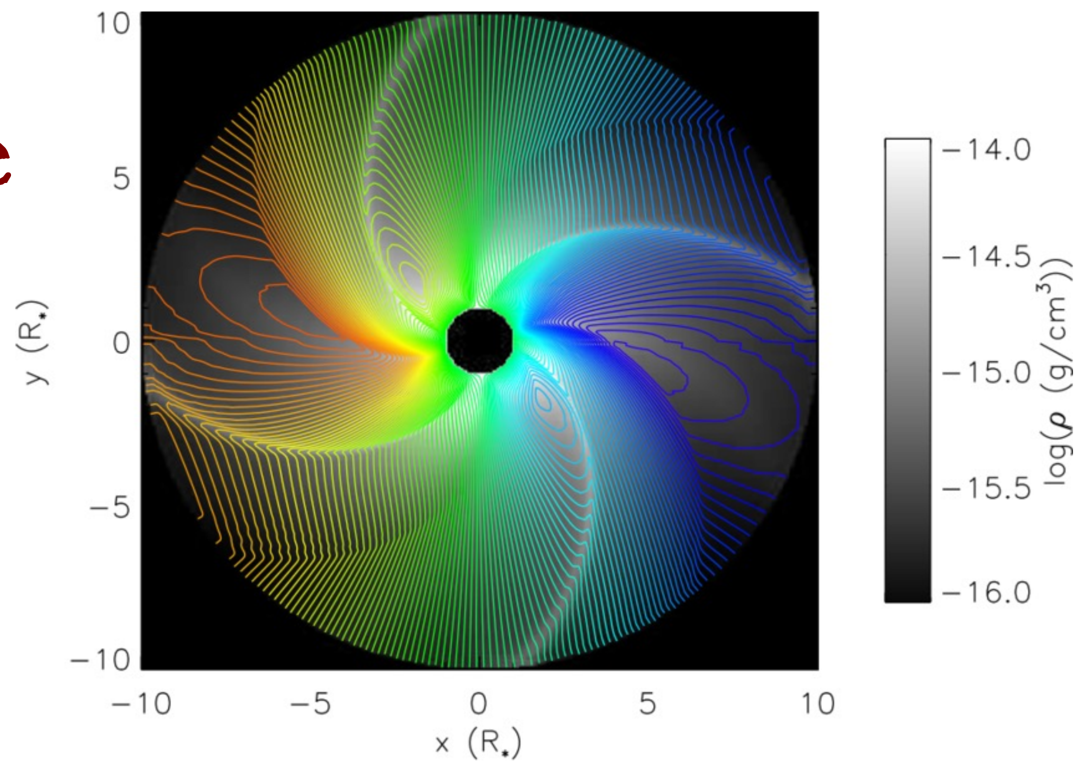
Structured Massive Star Winds: CIRs

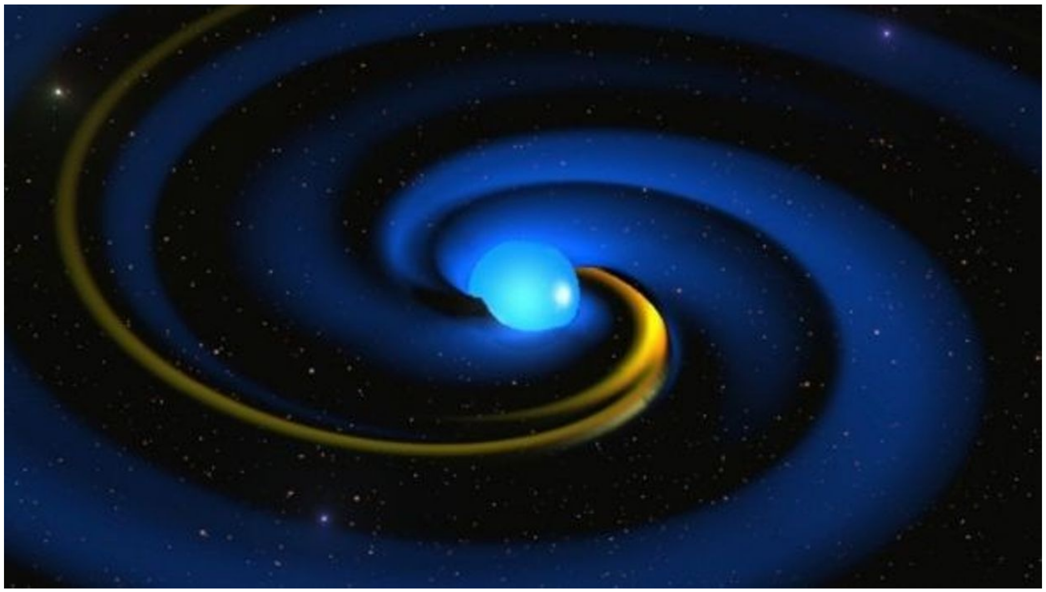
- **Top:** hydrodynamical simulation with four hot spots and four CIRs for flow in the equatorial plane

  (based on David-Uraz+ 2017)

- **Bottom:** artistic impression

(observer to the right)



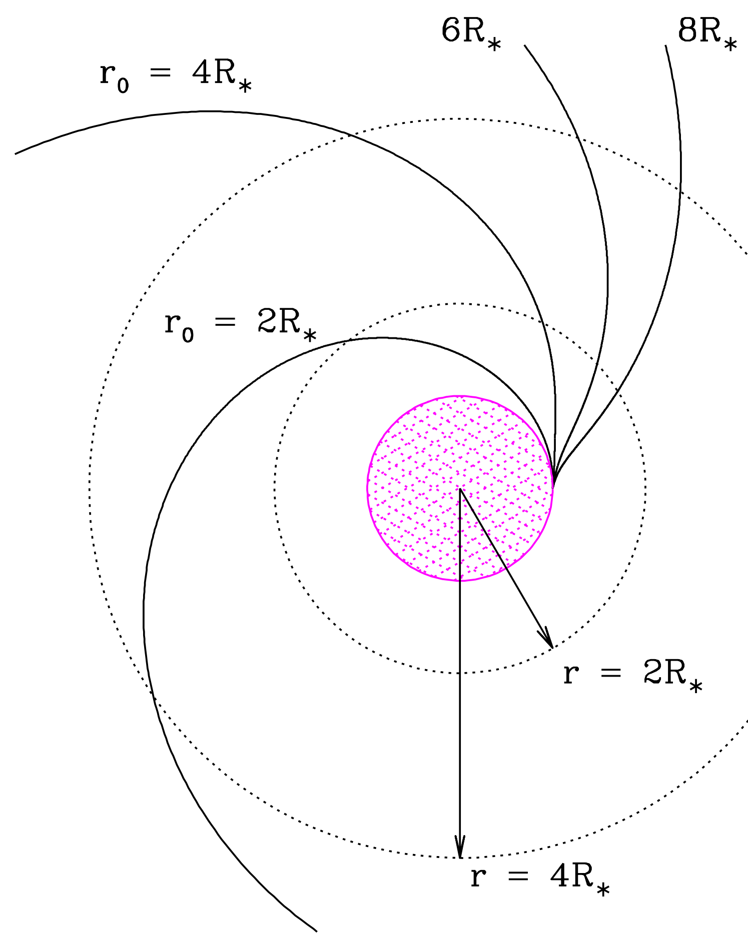


Testing Survival of CIRs

- Spherical wind
- Free-free opacity at long λ
- CIR of constant solid angle with density contrast superimposed
- Degree of spiral set by the "winding radius", which at the equator is

$$r_0/R_* = v_\infty/v_{rot}$$

- Detailed spiral shape set by an equation of motion for the wind in the co-rotating frame

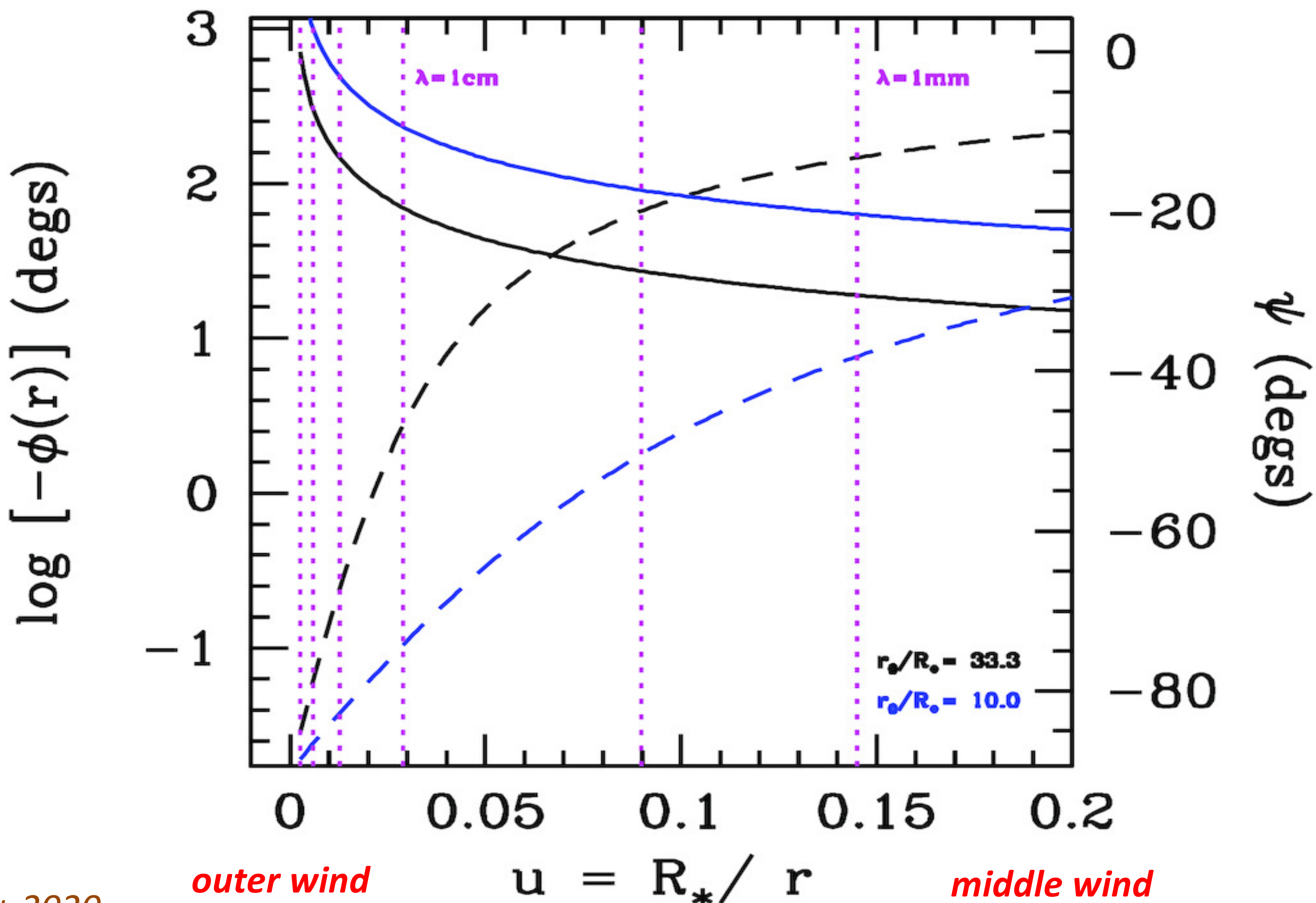


Rotation is clockwise

Ignace+ 2015

Left axis: (solid) Angle of wrapping (turns) of the CIR with inverse radius
Right axis: (dash) Pitch angle for the CIR tangent vector as backwinding

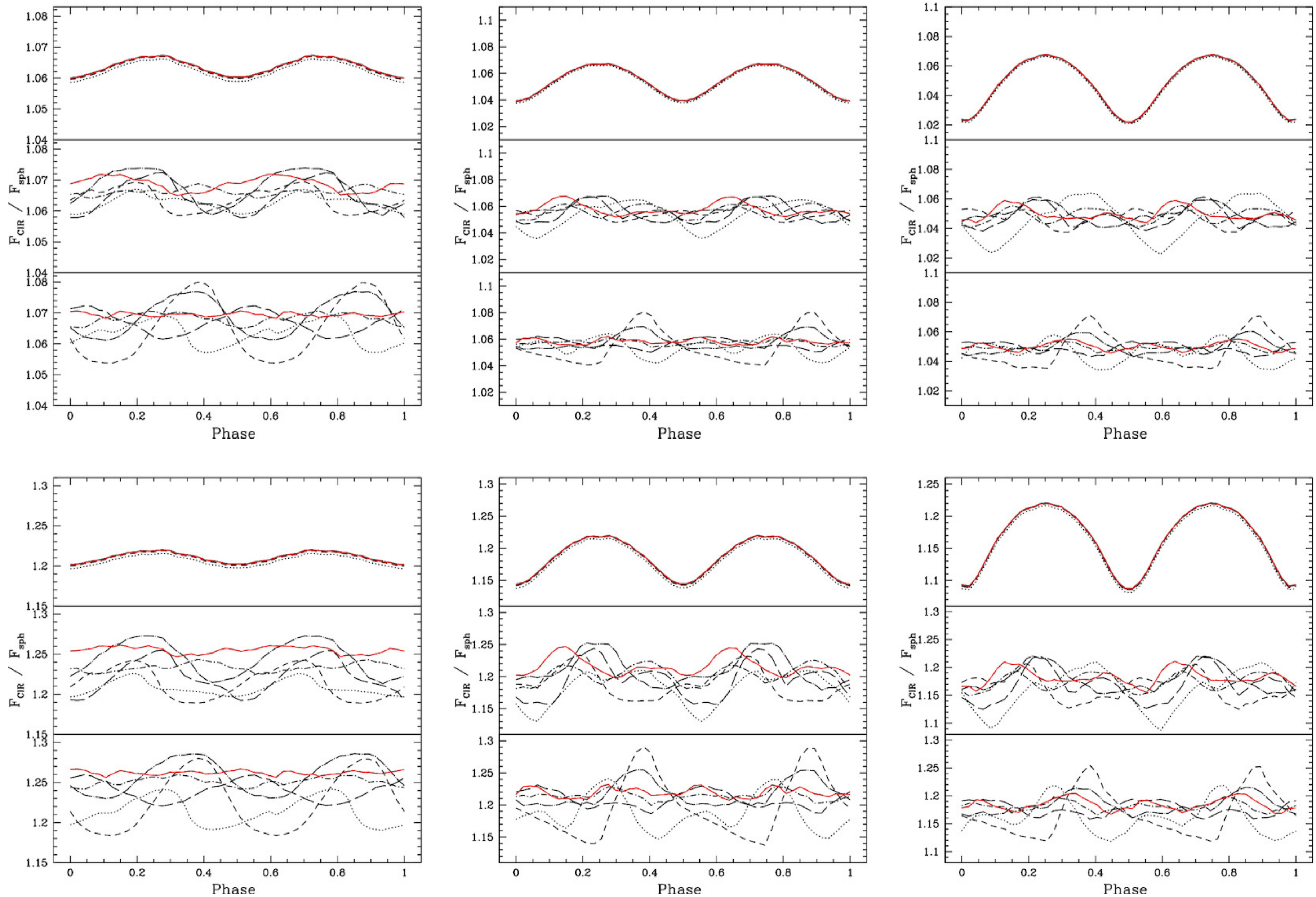
black and blue are different r_0 values; wavelengths for flux calculations



Ignace+ 2020

Opening angle of 25 deg; Upper set has a density contrast of 4; Lower a contrast of 10; Curves are different wavelengths with dotted for 1 mm and red for 31.6 cm

Inclination: 30 60 90

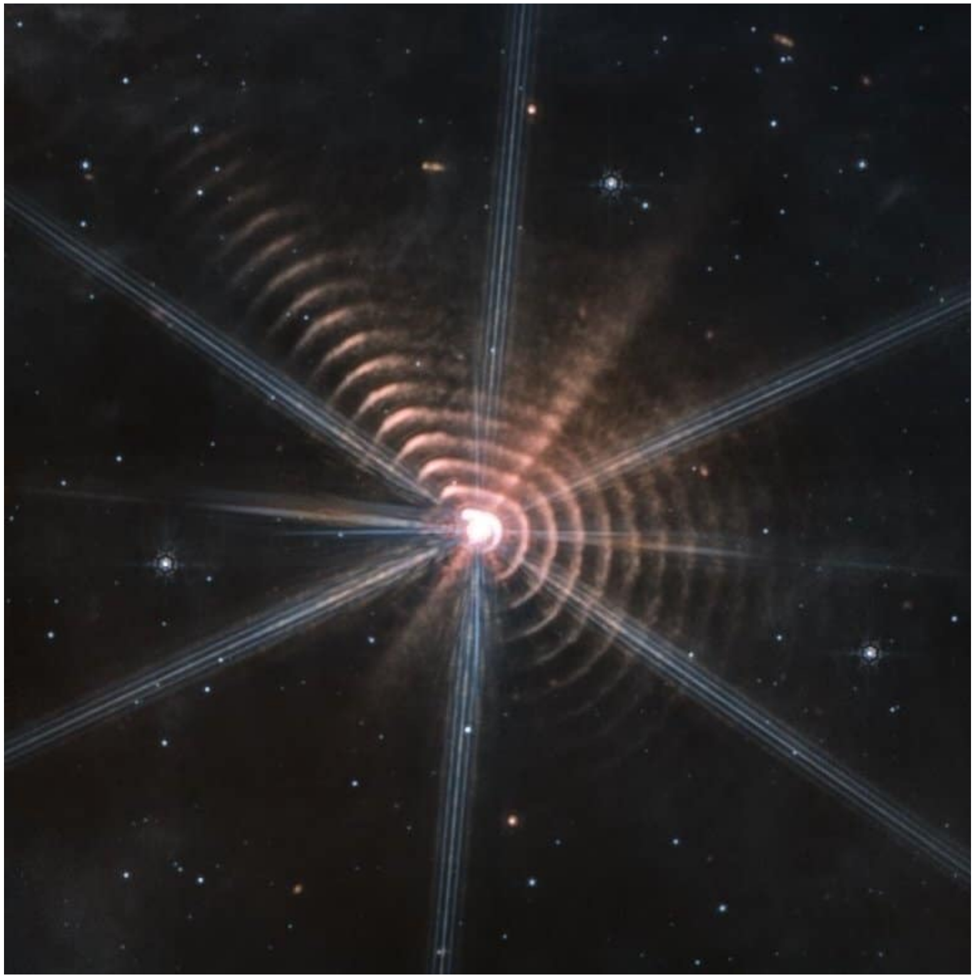


'Zero'
Slow
Fast

'Zero'
Slow
Fast

Structured Massive Star Winds: Binary colliding winds

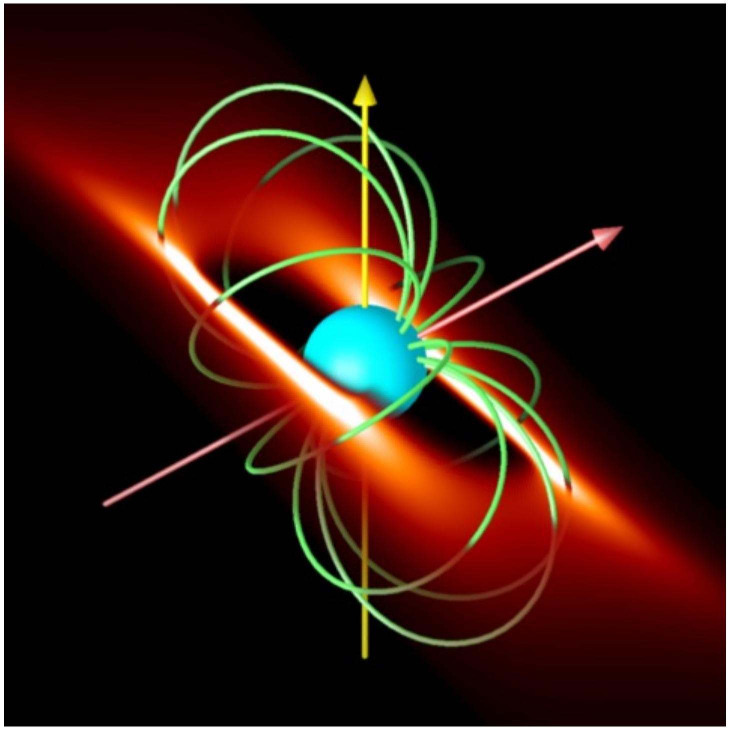
not ***covering binaries, but co-rotating interaction regions have some morphological similarities to colliding winds***



JWST imaging of WR140: *WC+O, P = 8 years; 17 shells (130 years)*
Lau+ 2022

Structured Massive Star Winds: Magnetospheric channeling

for a misaligned field, generally a warped and non-axisymmetric disk



RRM
(Townsend & Owocki 2005)

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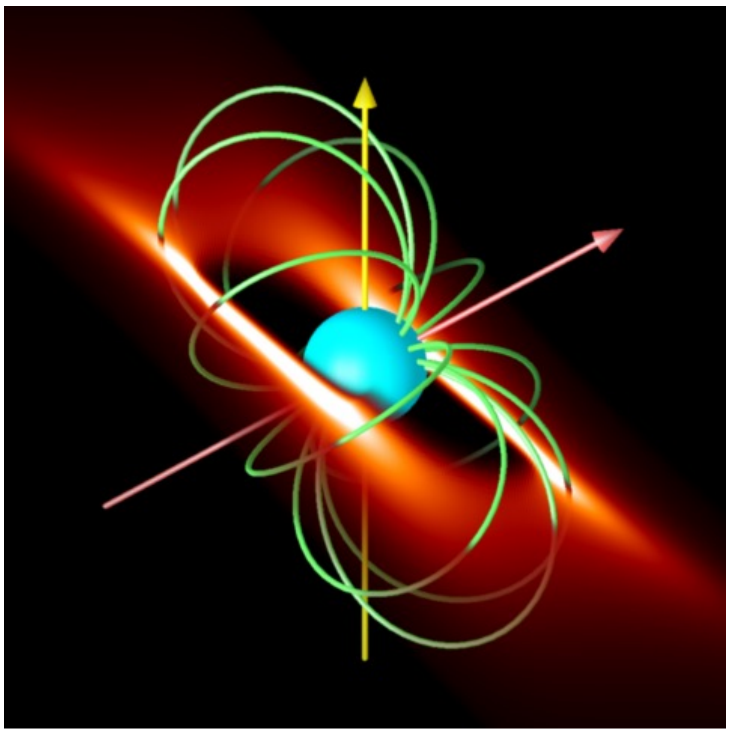

RRM
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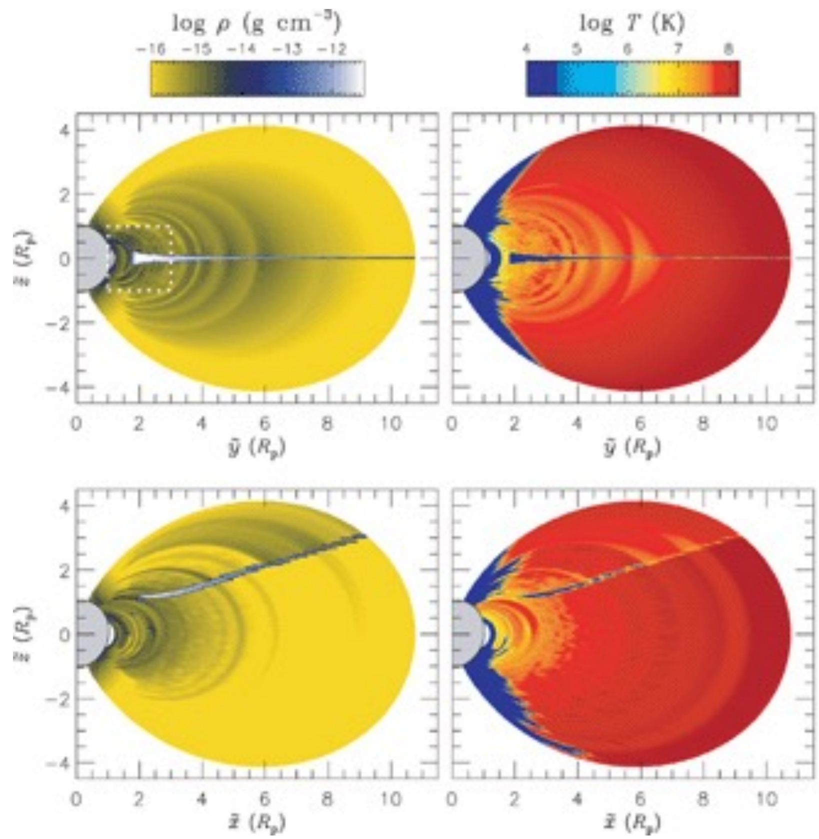
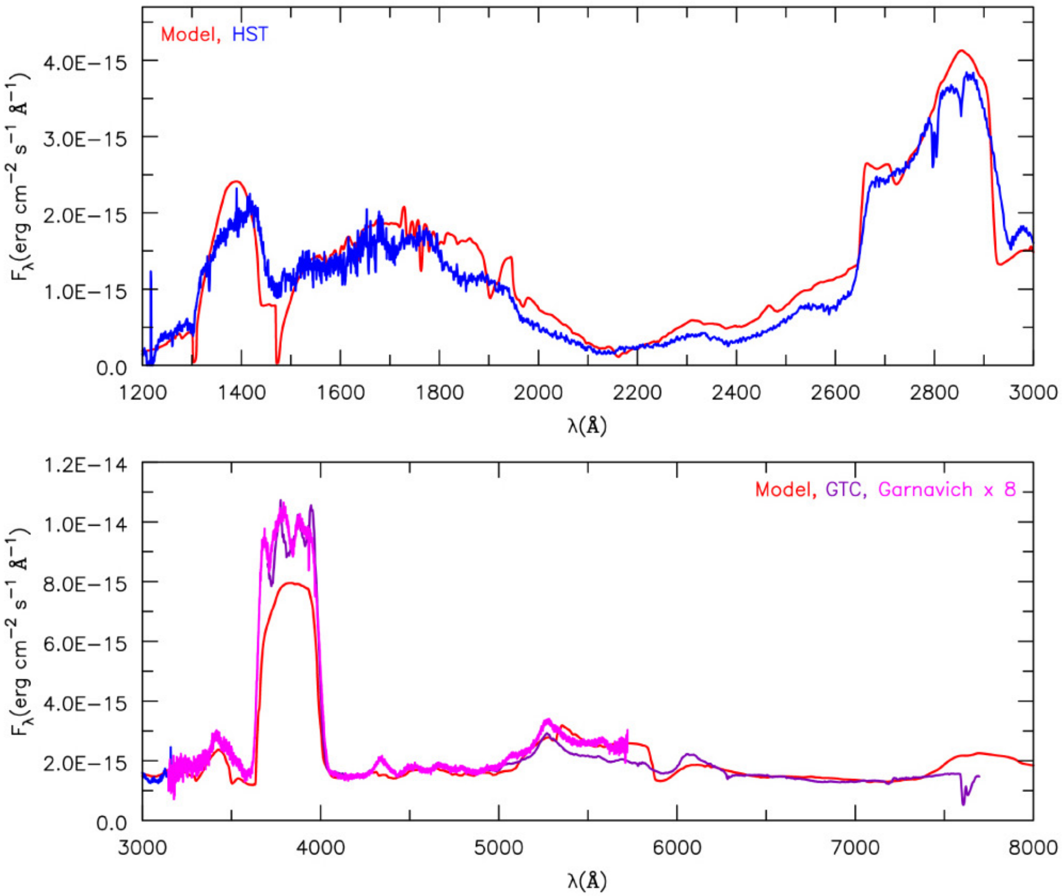
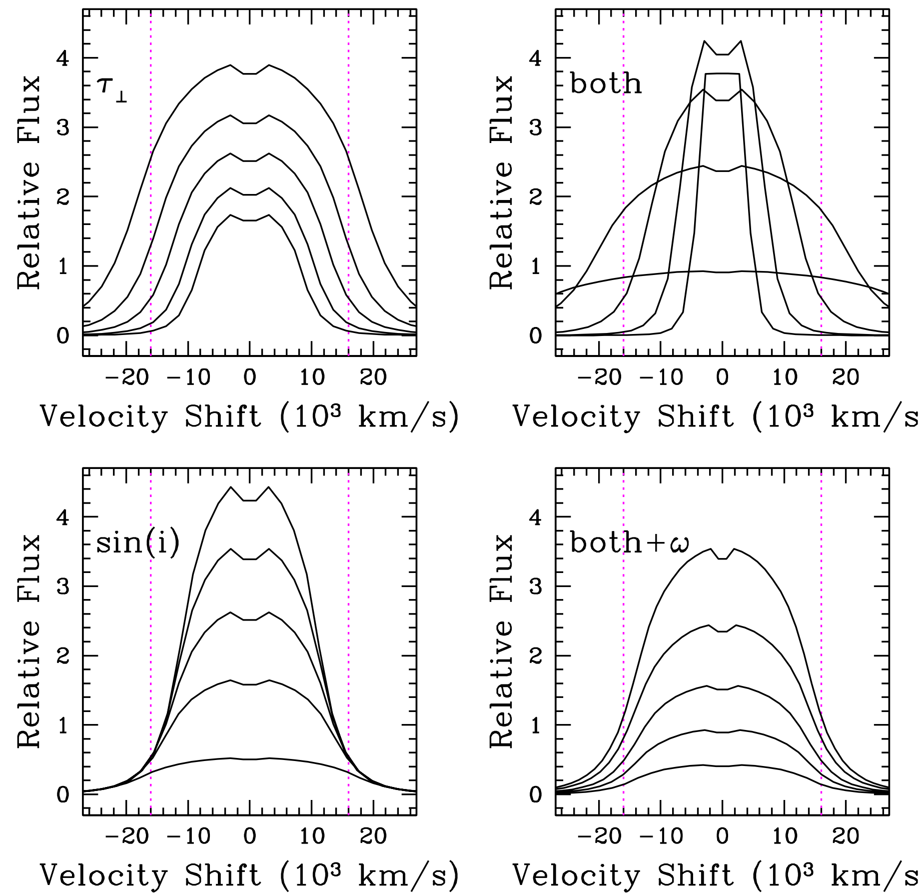


RFHD
(Townsend+ 2007)

UV/Optical Emission Lines with RRM

SN 2002cx-like; Type Iax





Lykou+ 2023

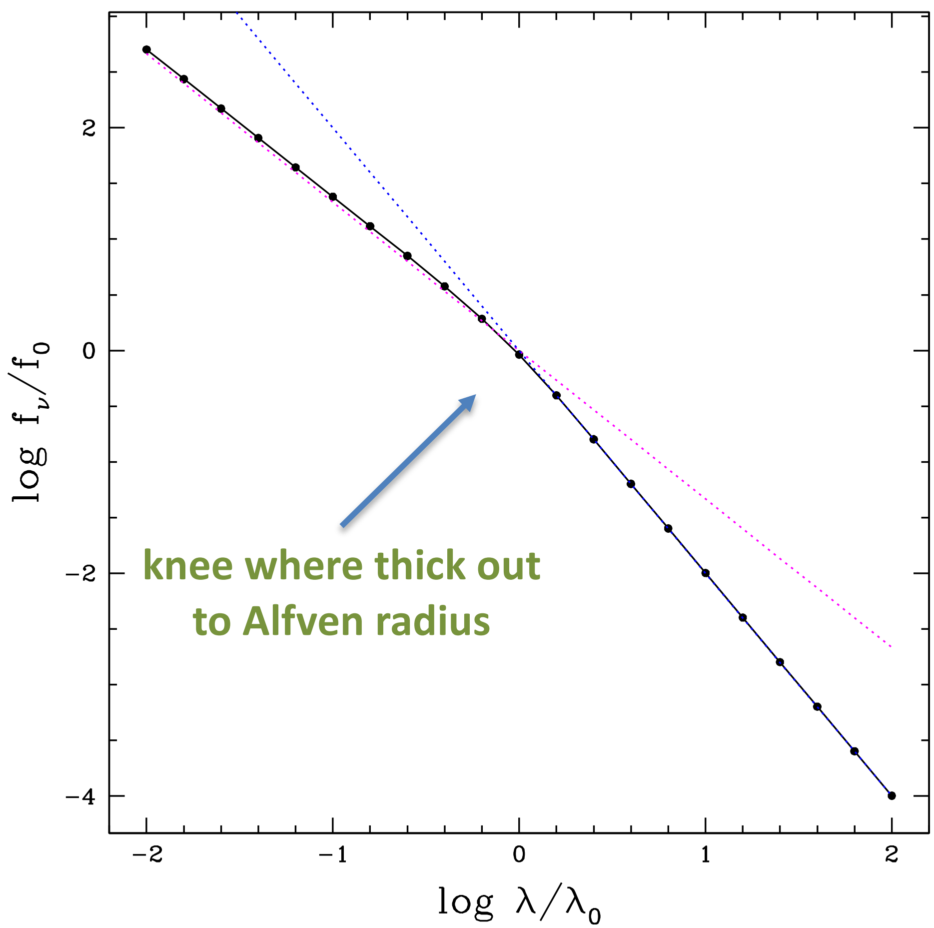
Model recombination line with RRM

Stellar remnant J005311
as double degenerate WD merger

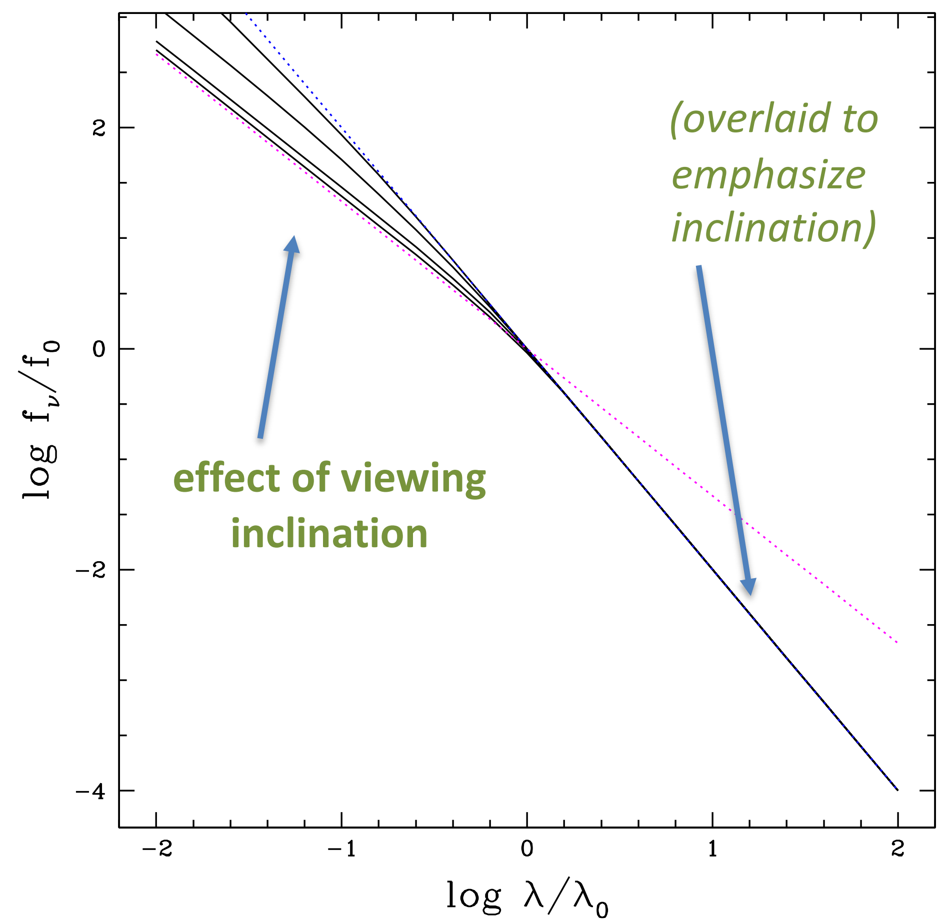
observed lines implied 15,000 km/s speed!

More Diagnostic Leverage: Free-free for RRM Disk

Assumes an aligned RRM model (Townsend & Owocki 2005)
Disk is "flat" (constant scale height) with a steep density gradient
Thermal emission via free-free
Extensive disk assuming strong surface field (motivated by WS35, WD merger)
Edge-on has analytic –4/3 power-law slope, changing to –2 when entirely thick



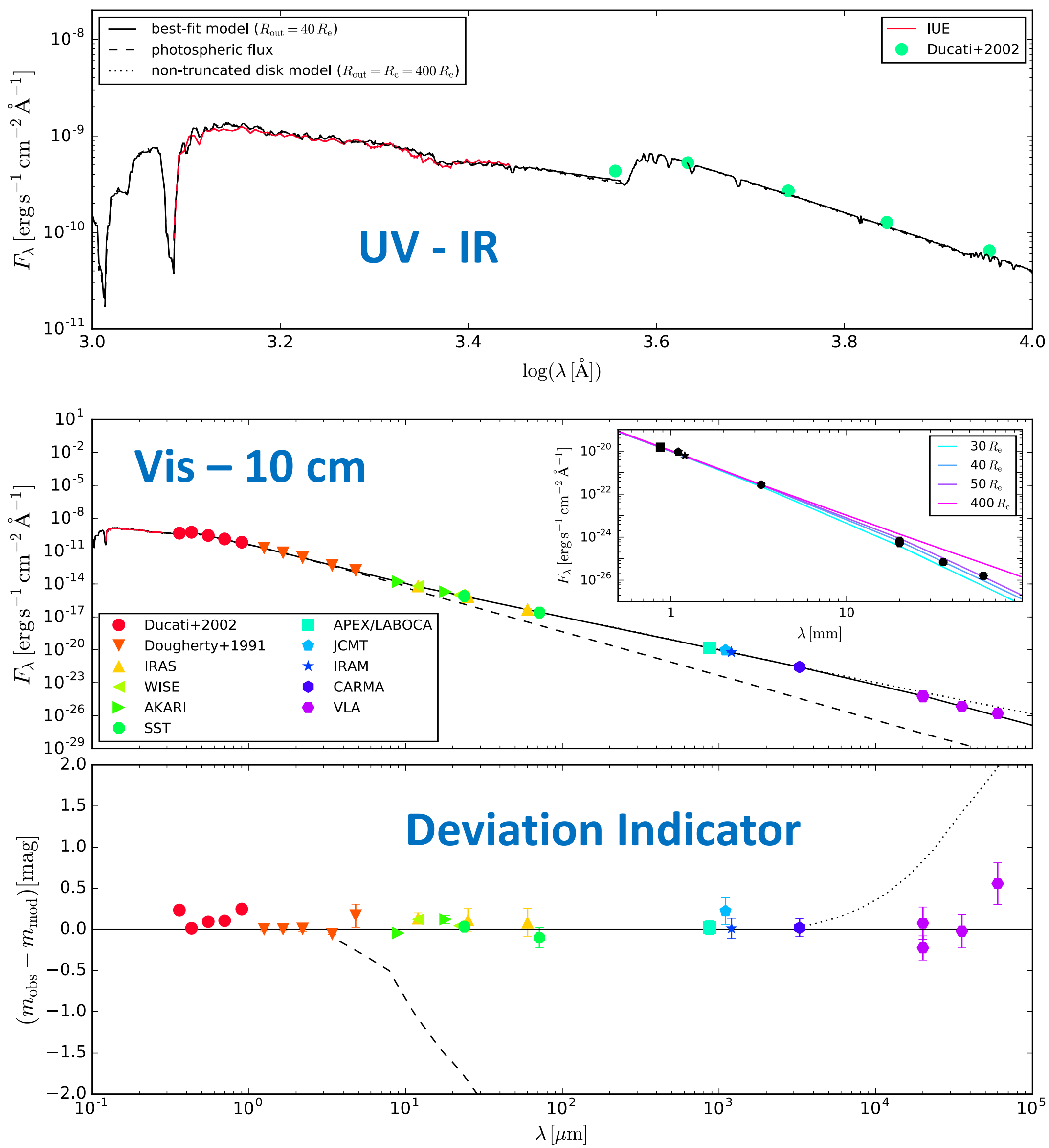
Edge-on



Inclination effects

(Aside: example of free-free and a "knee")

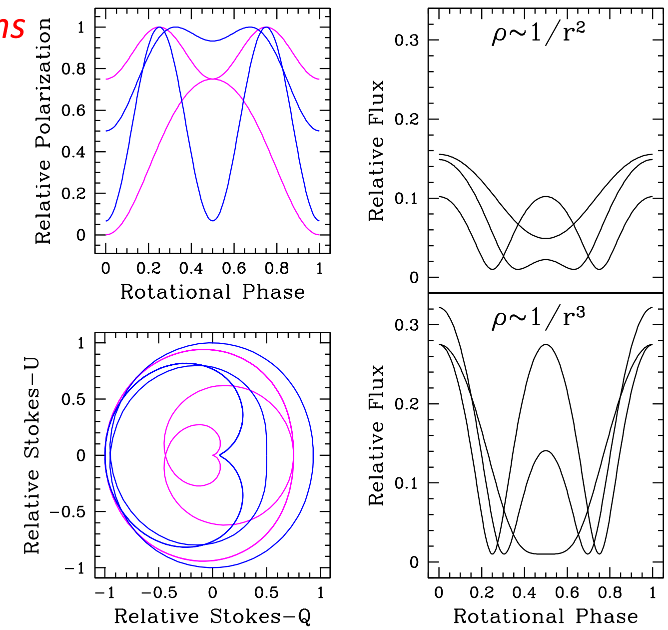
- Be stars are non-magnetic
- Be stars have extensive disks
- Be stars spin fast
- Long question of where disks dissipate or truncate
- Extensive study reveals SED slope change for good quality cases corresponding to dozens of stellar radii
- Likely indicator of companion (stripped core) clearing an annular region, with disk recovering outside the orbit



Klement+ 2017

May as well: Oblique Rotators in Radio & Polarization

mix of inclinations and obliquities



- Weak field gives a roughly axisymmetric wind
- Brown & McLean (1977) describe thin Thomson scattering polarization for an axisymmetric envelope

$$p(t) = \bar{\tau}\,(1-3\gamma)\,sin^2 i(t)$$

- Schmid-Burgk (1982) describes the free-free SED for axisymmetry
  - for power laws in density and temperature, the SED slope is the **same** as for a spherical wind ***(because slope relates to isophotal growth rate)***
  - however the luminosity level is a function of shape and inclination
  - for an ellipsoid of rotation, Schmid-Burgk shows

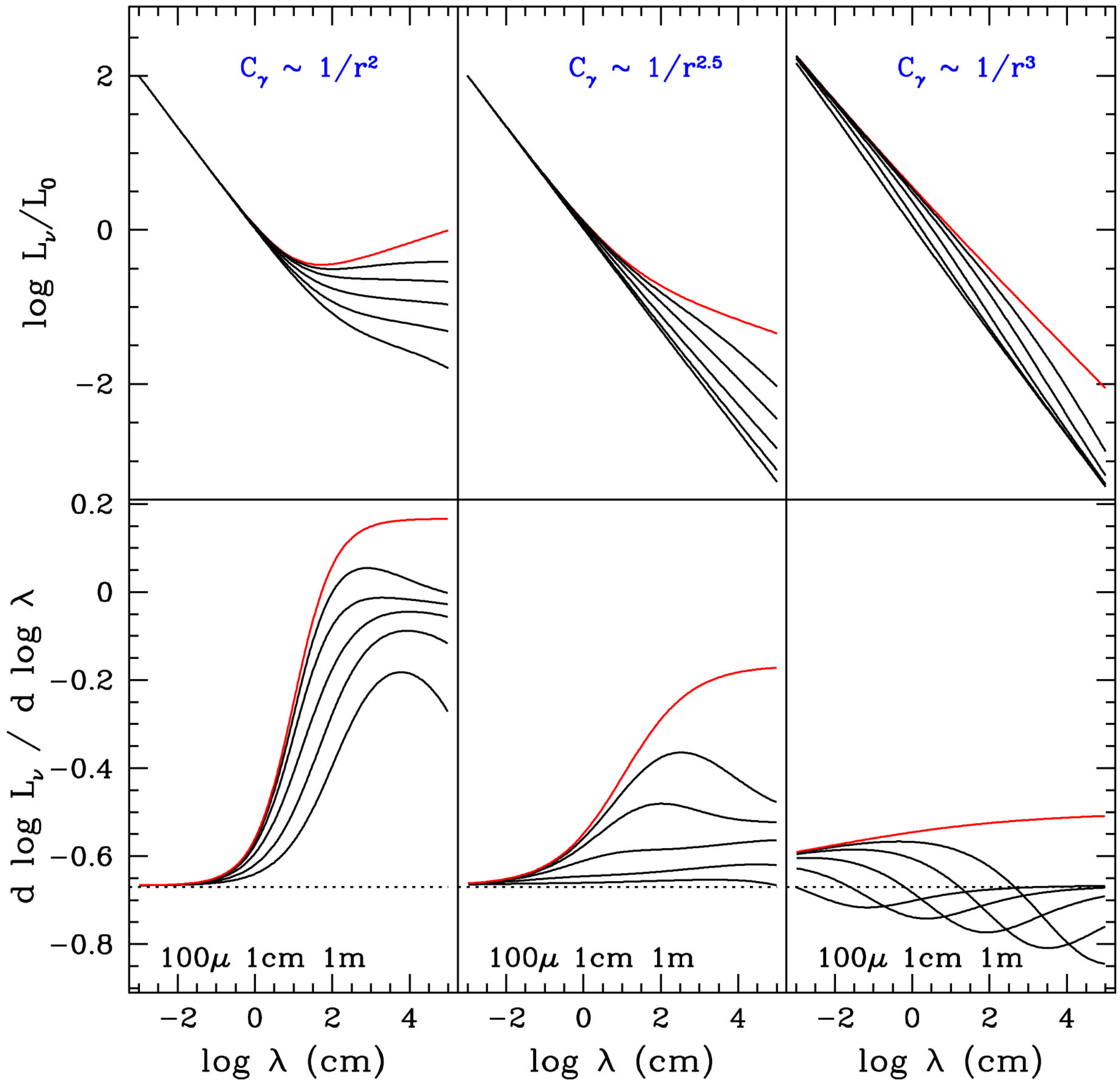
$$L_\lambda^{ff}(t) \propto [\,1-(1-\varepsilon^2)\,sin^2 i(t)\,]^{\frac{(2n-3)}{(4n-2)}} \sim [\,A \,+\, B\,p(t)\,]^{\frac{(2n-3)}{(4n-2)}}$$

Free-free with Synchrotron

Erba & Ignace 2022

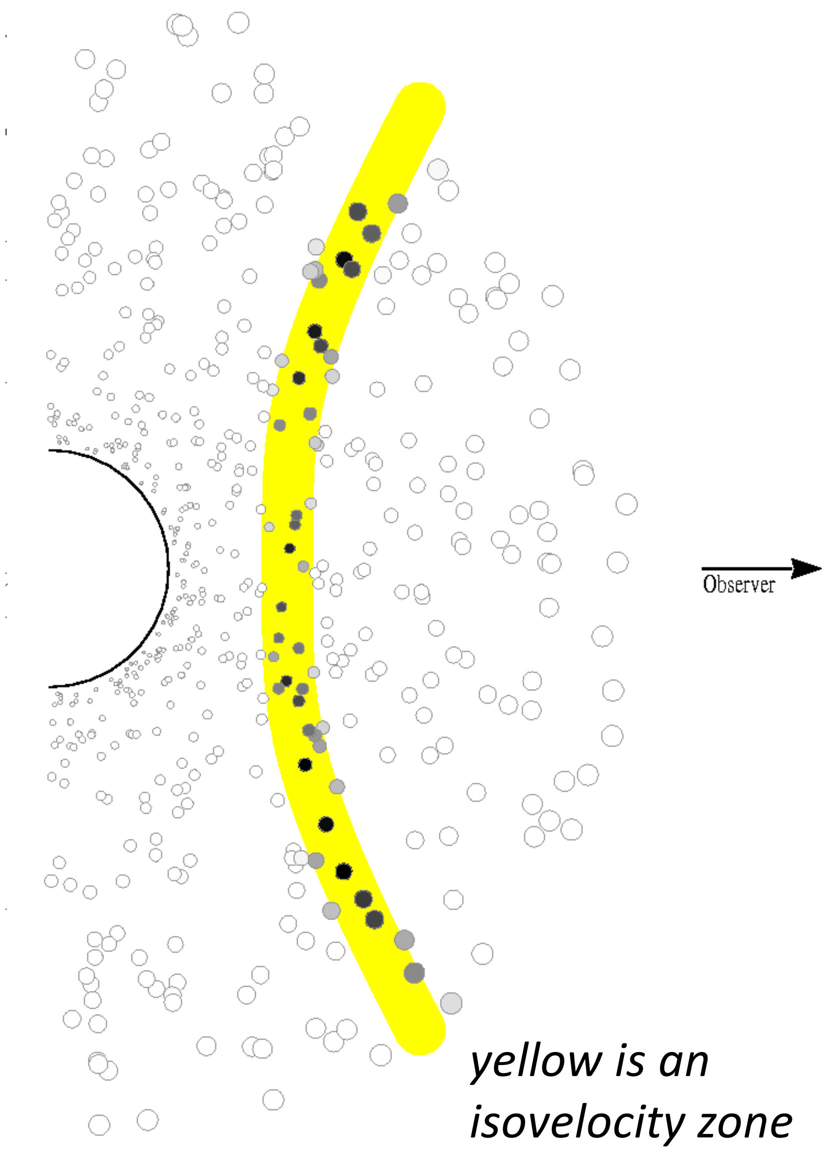
Spherical wind with free-free and synchrotron

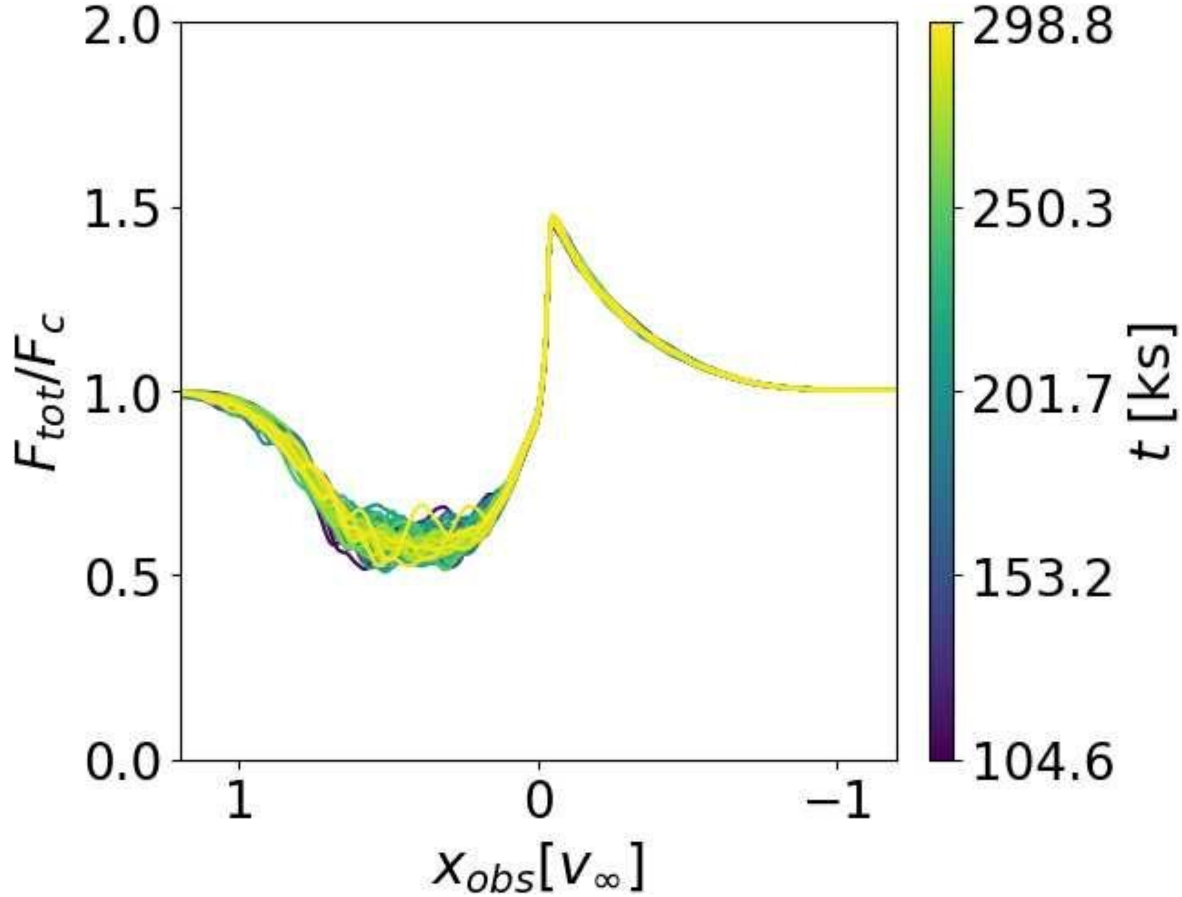
- Assume asymptotic field strength with B ~ 1/r
- "C_γ" refers to the radial distribution of relativistic particles *(where & how?!)*
- Curves for different stellar magnetic field strengths
- **Upper** is for SEDs
  Lower for run of power-law slopes
  (dotted is zero field)
- Razin effect included
  - as reference, red curves omit Razin



Structured Massive Star Winds: Clumpy Flow

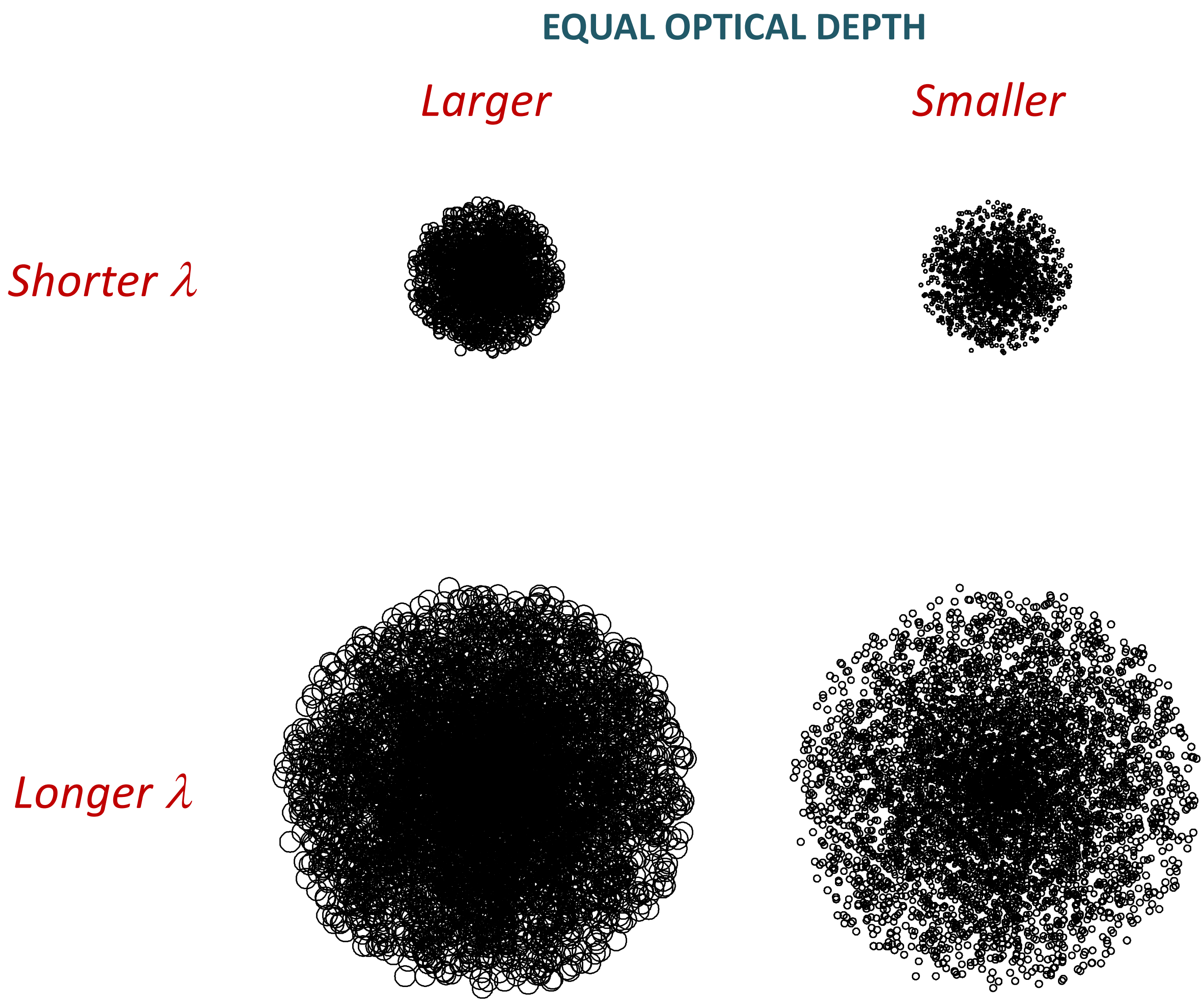
(Oskinova+ 2007)





(David-Uraz+ 2017)

Testing Survival of Clumps: Fluctuations



Outflowing spherical clumps that maintain identity are weird!

asymptotic $\rho \sim 1/r^2$
requires $V_c \sim 1/r^2$

So,

$R_c \sim r^{2/3}$

$\Omega_c \sim r^{4/3}$

Summary

Structured flow – whether wind, disks, magnetospheres, stochastic or organized – can be studied with multi-wavelength diagnostics to test theories and simulations.

Long-wavelength emissions play a central role in such studies through:

- **Exploring these with predictive diagnostics**
- **SED slope (thermal/non-thermal)**
- **SED variability (fluctuations/cyclic)**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Questions?
SARA's Jacobus Kapteyn Telescope in La Palma, 2016